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Short Tilte of Work: BROADBAND DISCRIMINATION STUDIES

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This research effort had three main objectives: 1) Use a newly developed method for the linear inversion of seismograms to study the source mechanism of explosions and earthquakes; 2) Continue the study of forward and inverse problems for wave propagation in a layered anaelastic earth; and 3) Study the bandwidth requirements of well-behaved discriminants.

A method has been developed which treats wave propagation in a layered anelastic medium in an exact manner. The method has been formulated for

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both body waves and surface waves and for both forward and inverse problems.

A general method of estimating the first-degree spatial moment tensor of a seismic source has been developed and applied to data recorded at the Nevada Test Site. Acceleration data recorded within a few kilometers of the explosion HANDLEY and a collapse event of the explosion JORUM have been studied. The explosion is predominantly a dilatation and the collapse is predominantly a compression and both are asymmetric in the vertical direction.

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1. Summary

This is the second technical report and also the final report for Grant No. AFOSR-78-3481. This research effort had three main objectives: 1) Use a newly developed method for the linear inversion of seismograms to study the source mechanism of explosions and earthquakes; 2) Continue the study of forward and inverse problems for wave propagation in a layered anelastic earth; and 3) Study the bandwidth requirements of well-behaved discriminants. Results pertaining to the second objective are contained in Technical Report No. 1 (24 July 1978), results pertaining to the first objective are contained in part 2 of the present report, and implications for the third objective can be found in both of these reports.

A method has been developed which treats wave propagation in a layered anelastic medium in an exact manner. These results are particularly important for problems which involve near surface sediments and soils because the approximate methods which are normally used for anelastic wave propagation are insufficient for these highly attenuating materials. The method has been developed for both body waves and surface waves and for both forward and inverse problems. The advantages of the exact over the approximate formulation appear to be most important in the inverse problems.

A general method of estimating the first-degree spatial moment tensor of a seismic source has been developed and applied to data recorded at the Nevada Test Site. Acceleration data recorded within a few kilometers

of the explosion HANDLEY and a collapse event of the explosion JORUM have been studied so far. The explosion is predominantly a dilatation with an asymmetry in the vertical direction which may represent the effect of the free surface. The time history is an initial step with a rise time less than half a second followed by a larger pulse with a slower rise time. This second pulse may also be related to the effect of the free surface. The collapse event is predominantly a compression and is also asymmetric in the vertical direction. The time history has a much more gradual beginning and a longer rise time than in the case of the explosion.

The use of broadband data was crucial in the two general studies completed under this grant. Even so, in both cases there were indications that better results might have been obtained if the bandwidth of the data had been greater.

2. Moment Tensors for an NTS Explosion and Collapse

One of the objectives of this research effort has been to continue our study of the manner in which elastic waves are generated near an underground explosion. This has been pursued by attempting to model broadband acceleration seismograms obtained at distances of a few km from explosions at the Nevada Test Site. Below we describe the results that were obtained for the explosion HANDLEY and for a collapse event of the explosion JORUM.

Figure 1 shows the deployment of the accelerometers. Each insturment site consisted of three components of force-balance accelerometers which had a flat response to acceleration in the band from 0 to 80 Hz. The analysis was performed on digital data with a four-pole low-pass anti-alias filter at 10 Hz and a sample rate of 54 samples per second.

The method of analysis is that described by Stump and Johnson (Bull. Seism. Soc. Am., 67, 1489-1502, 1977). It is assumed that the wavelengths of interest are long compared to the source dimensions so that the displacement can be represented as

$$u_k(x,t) = G_{ki,j}(x,t;0,0) \circledast M_{ij}(0,t)$$

where G_{ki} is the elastodynamic Green's function, M_{ij} is the first-degree spatial moment tensor of the source, and $\circledast$ denotes temporal convolution. In this study a homogeneous elastic halfspace was assumed in calculating the Green's function G_{ki}. Given these Green's functions and the observational data u_k, one can estimate the six independent components of the second-rank

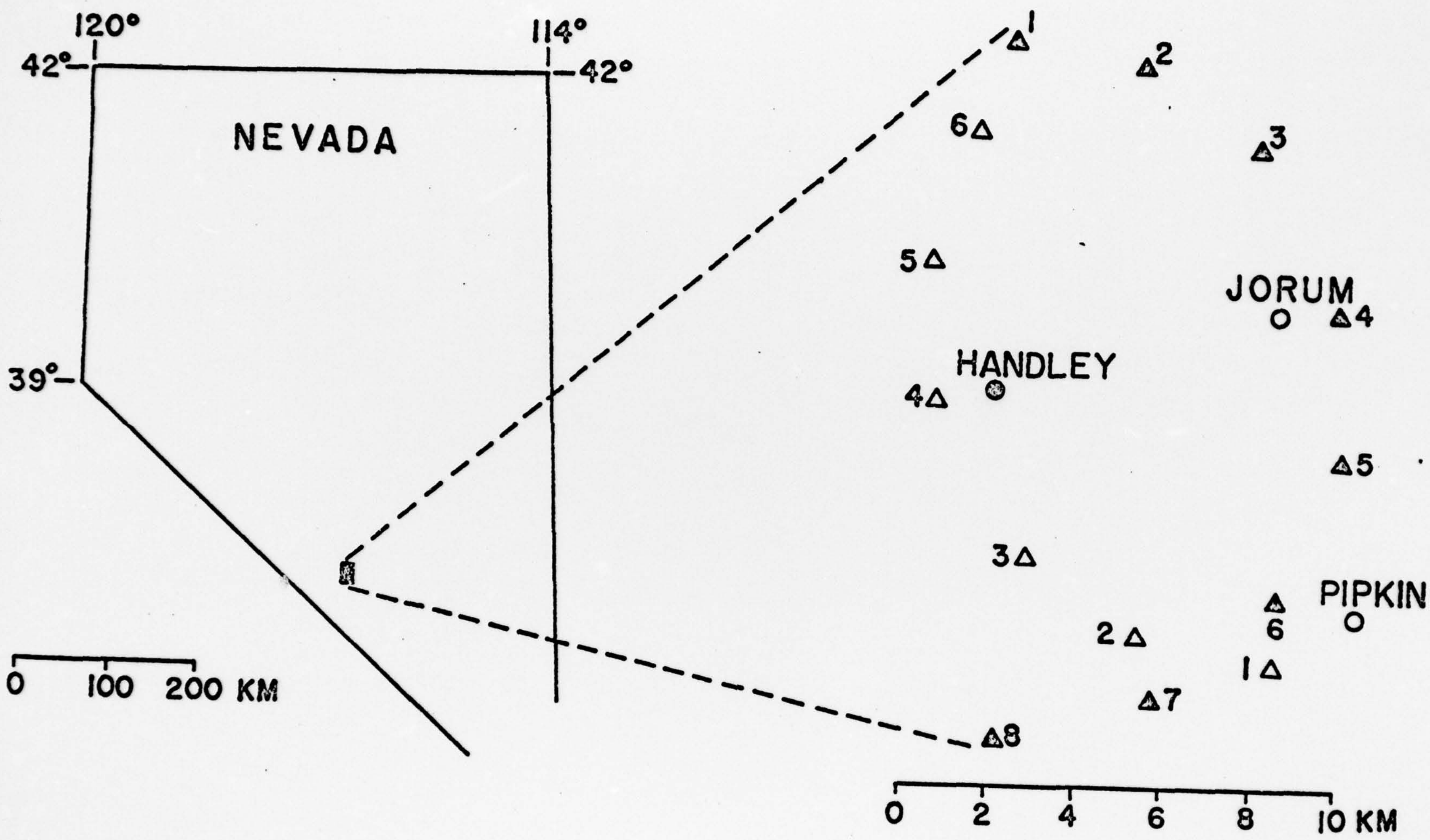

Figure 1. Location of the recording sites. The open triangles denote the instrument sites that were occupied for the explosions JORUM and PIPKIN while the solid triangles denote the instrument sites that were occupied for the explosion HANDLEY.

symmetric moment tensor M_{ij}.

The explosion HANDLEY was detonated on 26 March 1970 in tuff at a depth of 1206 meters below the surface and 819 meters below the water table. Its Wood-Anderson magnitde was 6.3. Good data were obtained from the sites 1, 2, 4, and 5 shown in Figure 1 and the acceleration records are reproduced in Figure 2.

The data in Figure 2 were inverted using a Green's function for a homogeneous halfspace to obtain an estimate for the moment tensor of the source. The spectra of the time derivative of these estimates of the moment tensor components are shown in Figure 3. Also shown is the spectra of the time derivative of the trace of the moment tensor, which is usually taken to represent the explosive part or more precisely the isotropic part of the source.

The results in Figure 3 exhibit a corner frequency of about 4 Hz and a high frequency slope of about -3. Also note that there is a gradual rise in the spectra at the lowest frequencies. The diagonal components of the moment tensor are considerably larger than the off-diagonal components (note the change in scale) and the M_{33} component is slightly larger than the other two diagonal components. The fact that the M_{12} component is very small plus the fact that the M_{11} and M_{22} components are nearly equal is an indication that the amount of strike-slip motion in the source is very small.

The phase corresponding to the modulus plotted in Figure 3 was also estimated so the components of the moment tensor can also be plotted in the time domain, as is done in Figure 4. A number of general conclusions

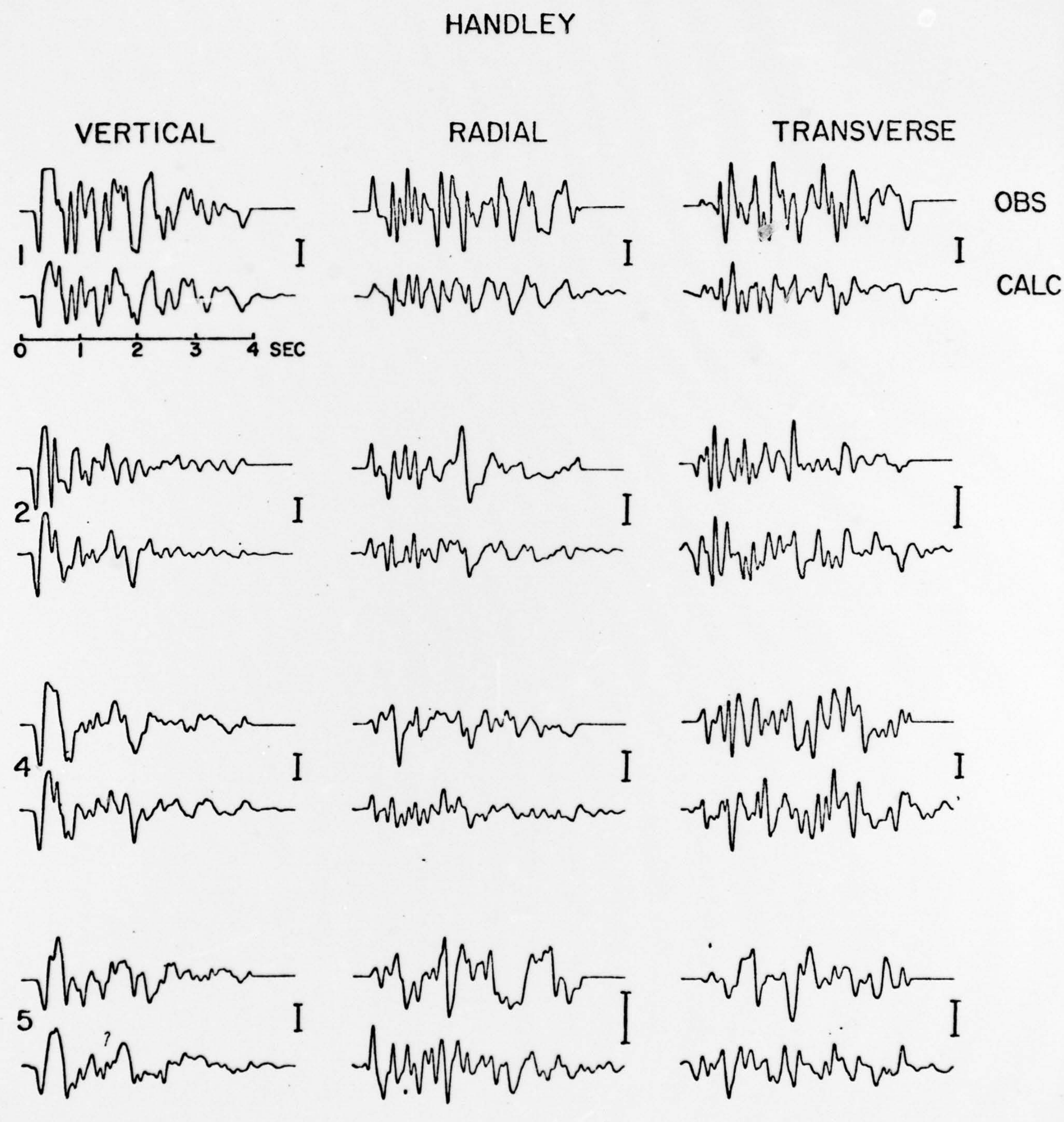

Figure 2. Three-component acceleration data from sites 1, 2, 4, and 5 for the explosion HANDLEY. In each case the upper trace is the observed data and the lower trace is that calculated from the source model derived in this study for HANDLEY. The vertical bar represents an amplitude scale which has the same value in every case.

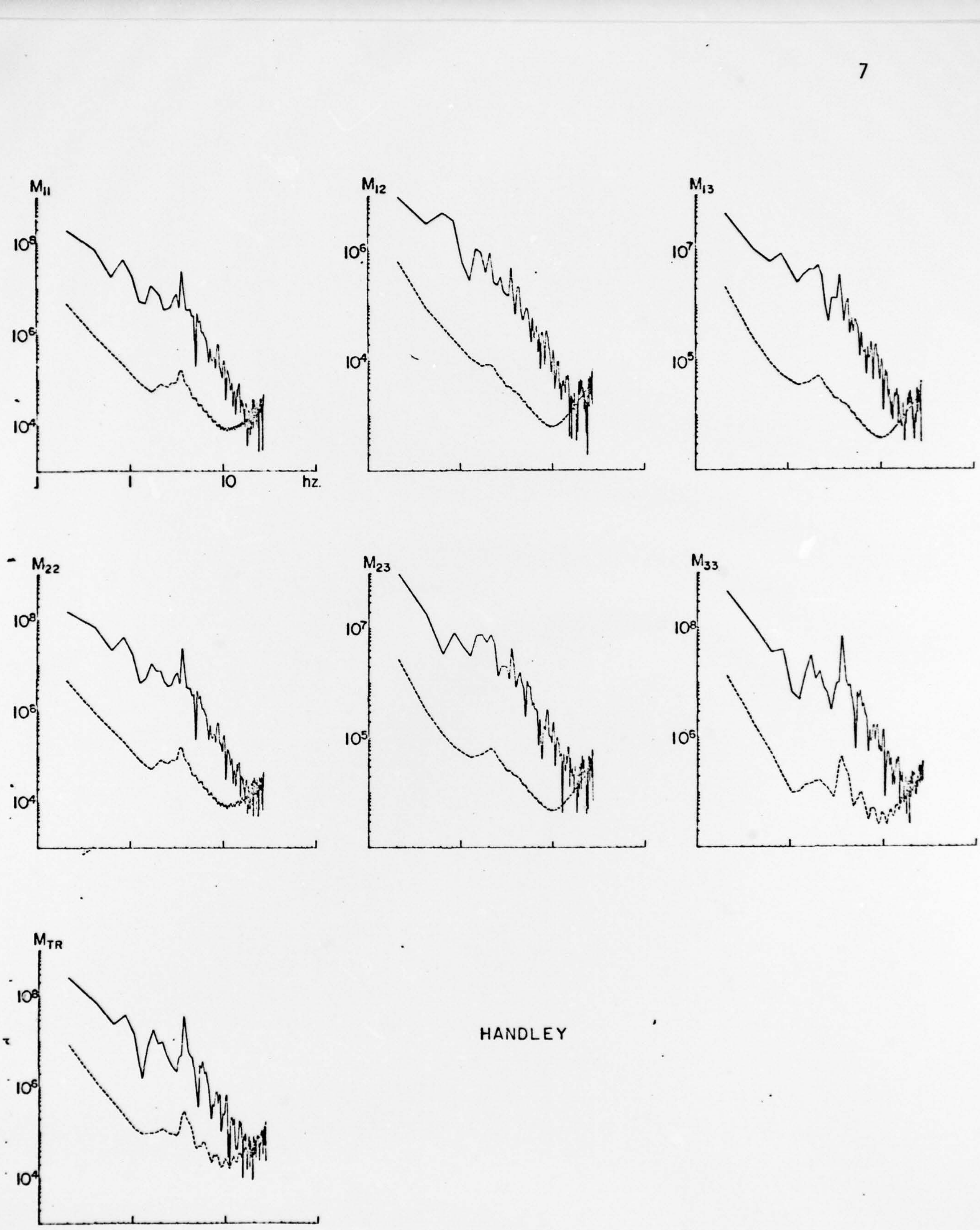

Figure 3. Amplitude density spectra (solid lines) of the components of the first time derivative of the moment tensor estimated for the explosion HANDLEY plus estimates of the standard deviation (dashed lines). The spectrum at the bottom is for the trace of the moment tensor.

follow from Figure 4. The diagonal components of the moment tensor are much larger than the off-diagonal components. The M_{33} component is larger than the M_{11} and M_{22} components so the source is not completely isotropic. A physical model to explain this might be an explosion in which the expansion in the verical direction exceeds that in the horizontal directions. In view of the vertical stratification of the medium and the presence of the free surface, such an asymmetry is not unreasonable.

The 3 Hz oscillation evident on the time derivative of the moment tensor in Figure 4 is due to a spectral peak of this frequency in the results of Figure 3 and can be traced back to a hole in the Green's function used in the inversion. Such a hole would be unlikely in a Green's function for a more realistic crustal structure, and thus little importance should be given to this oscillation.

The diagonal components of the moment tensor shown in Figure 4 all have approximately the same shape. It consists of an initial dilatation with a rise time of less than half a second followed by a much larger dilatation beginning about 1 second after the origin time and rising to a maximum about 3 seconds after the origin time. There is an apparent decrease beyond 3 seconds but this may be an effect of limited resolution at the low frequencies.

The shape of the very low frequencies of the moment tensor spectra (Figure 3) was an interesting result which was investigated further. This trend in the results can be traced back to the original data (Figure 2) where it may be related to the fact that the data were all recorded with accelerometers which have relatively less resolution at the low frequencies compared to the high frequencies. To determine the influence

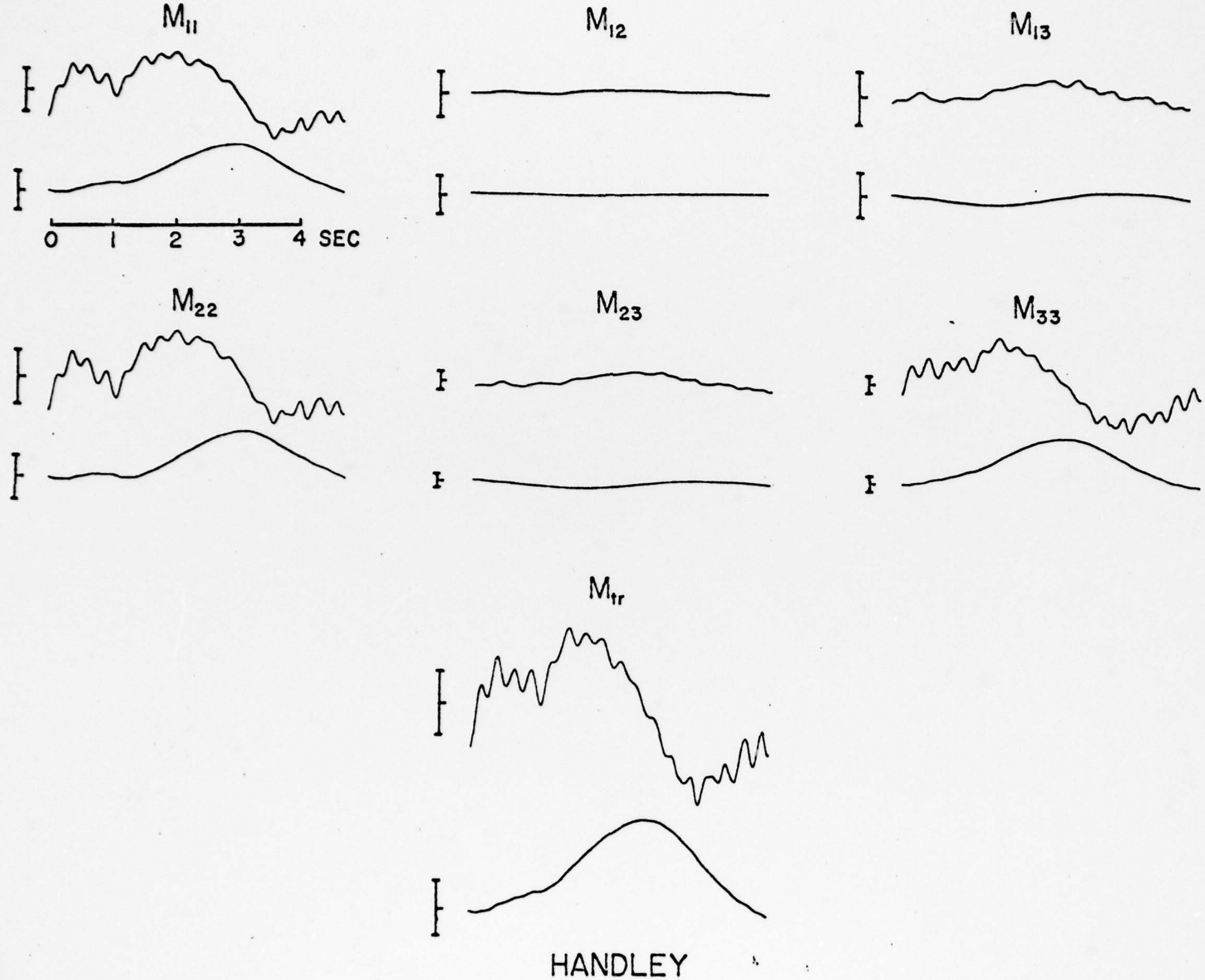

Figure 4. Estimates of the components of the moment tensor for HANDLEY in the time domain. The lower member of each pair is the component of the moment tensor and the upper member is its time derivative. Similar results for the trace of the moment tensor are shown at the bottom. The vertical bar represents an amplitude scale which has the same value in every case.

of this trend in the low frequencies, it was removed by high-pass filtering the data to the extent that the spectra were approxomately flat at the low frequencies. Then the entire inversion process was repeated to obtain the results shown in Figure 5. Comparing these results with those in Figure 4 shows that, as one might expect, only the long period part of the results has been affected. Thus Figures 4 and 5 represent two versions of the moment tensor, depending upon whether the long period trend in the data is considered to be real or spurious.

This general problem of the long period trend in the data is still not satisfactorily resolved and needs further study. One approach is to record the data with both acceleration and displacement responses so as to broaden the frequency band where good resolution is achieved. Another approach is to increase the dynamic range of the acceleration recording system.

A common method of judging the validity of a source model is to compare the synthetic data predicted by this model with the observed data. This is done for the method of this report in Figure 2 where the lower member of each pair was calculated by combining the source model in Figures 3 and 4 with the Green's function of a homogeneous halfspace. Although there are some obvious discrepancies, the agreement is not unreasonable and is actually quite good on the vertical components. An important point is that many of the features of fairly complex acceleration seismograms can be explained with a very simple source and crustal model. On the other hand, it has not been shown that this is a unique interpretation.

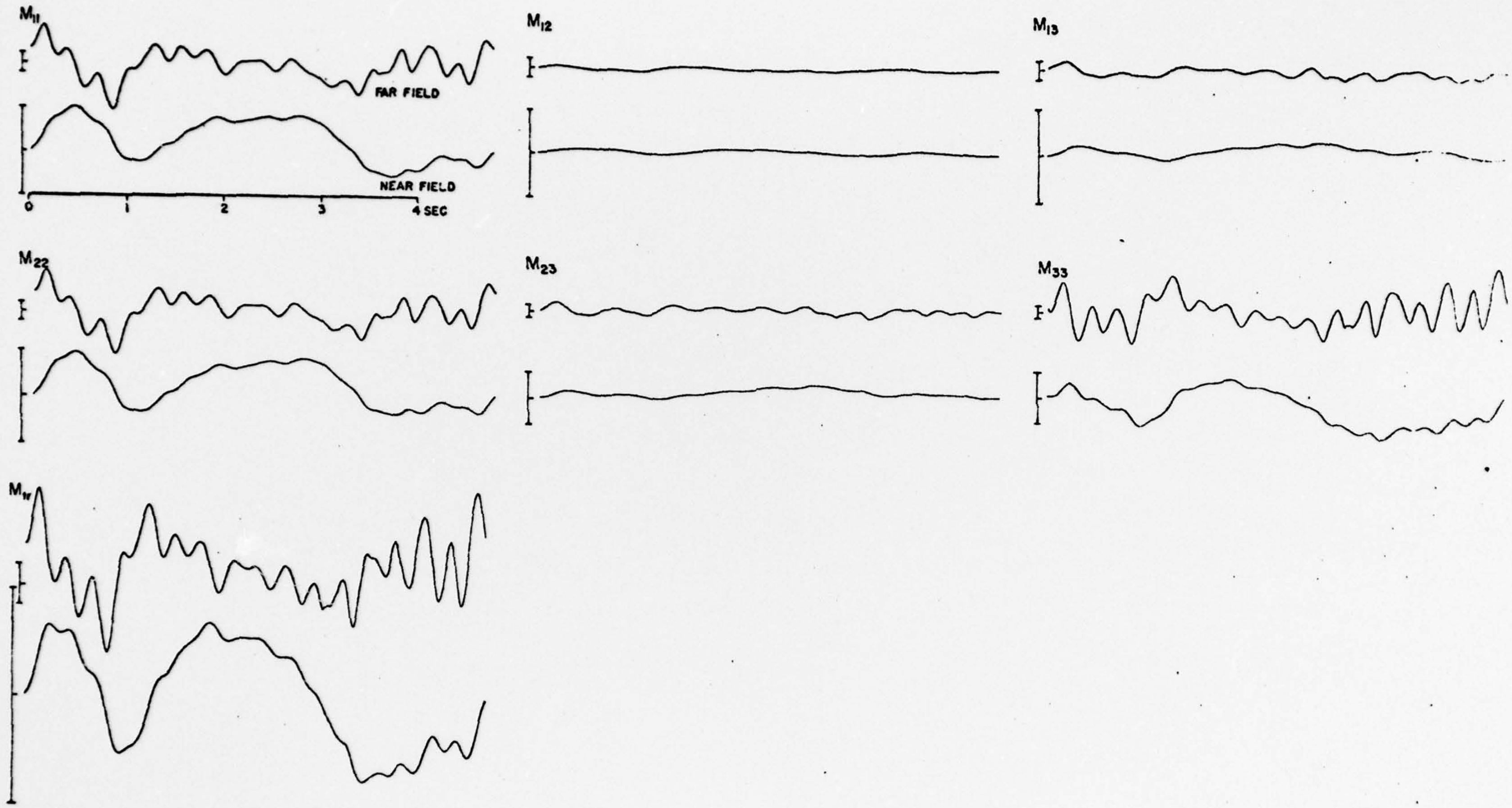

Figure 5. Same as Figure 4 except the data have been high-pass filtered to obtain essentally flat low-frequency spectra before the inversion process is applied.

As a further attempt to test our method of studying seismic sources, it was applied to a collapse event of the explosion JORUM. The deployment of the recording stations is shown in Figure 1. The collapse occurred at 17h 31m on 16 September 1969 which was about 3 hours after the JORUM event. The collapse was located within 80 m of the initial explosion which was in tuff at a depth of 570 m. The Wood-Anderson magnitude of the collapse was 4.3. The data recorded by the six stations which successfully recorded the collapse are shown in Figure 6.

The data in Figure 6 are quite different from those of an explosion such as Figure 2. The beginning is emergent, there are no clear phases, and the duration is longer than for an explosion.

The results of applying the inversion process to the collapse data are shown in the frequency domain in Figure 7 and in the time domain in Figure 8. A comparison of the moment tensor for the collapse and explosion (Figures 8 and 4) reveals both similarities and differences. The diagonal terms of the moment tensor for the collapse are dominant as in the case of the explosion but now they have the opposite sign. Thus the collapse appears to be an implosion, just as one might expect. Again the M_{33} component is larger than the M_{11} and M_{22} components which indicates an asymmetry in the vertical direction. The time function for the collapse has a much more gradual beginning and a much longer rise time than in the case of the explosion (note the difference in time scales in Figures 8 and 4).

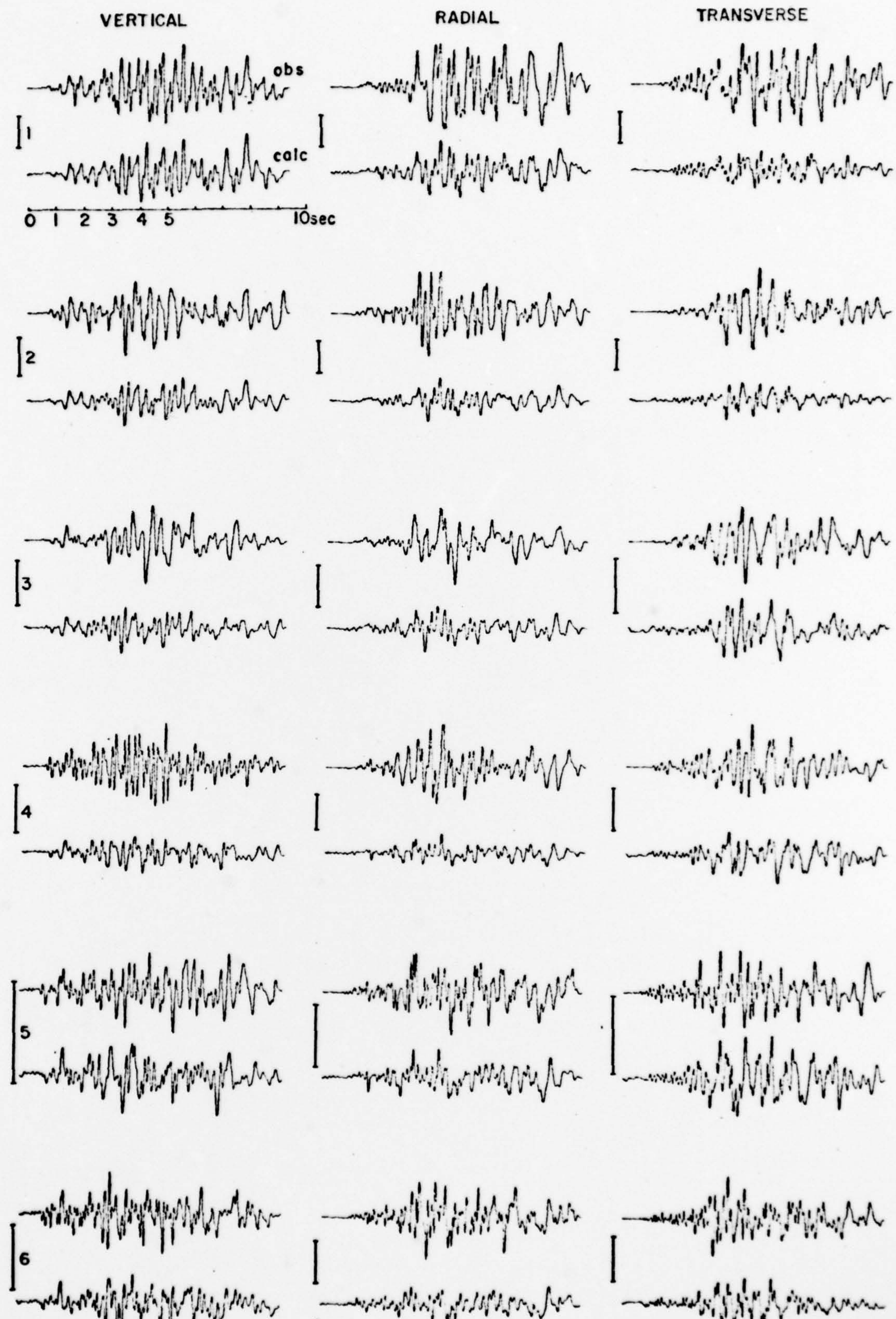

Figure 6. Three-component acceleration data from sites 1-6 for a collapse event of the explosion JORUM. In each case the upper seismogram is observed and the bottom is calculated.

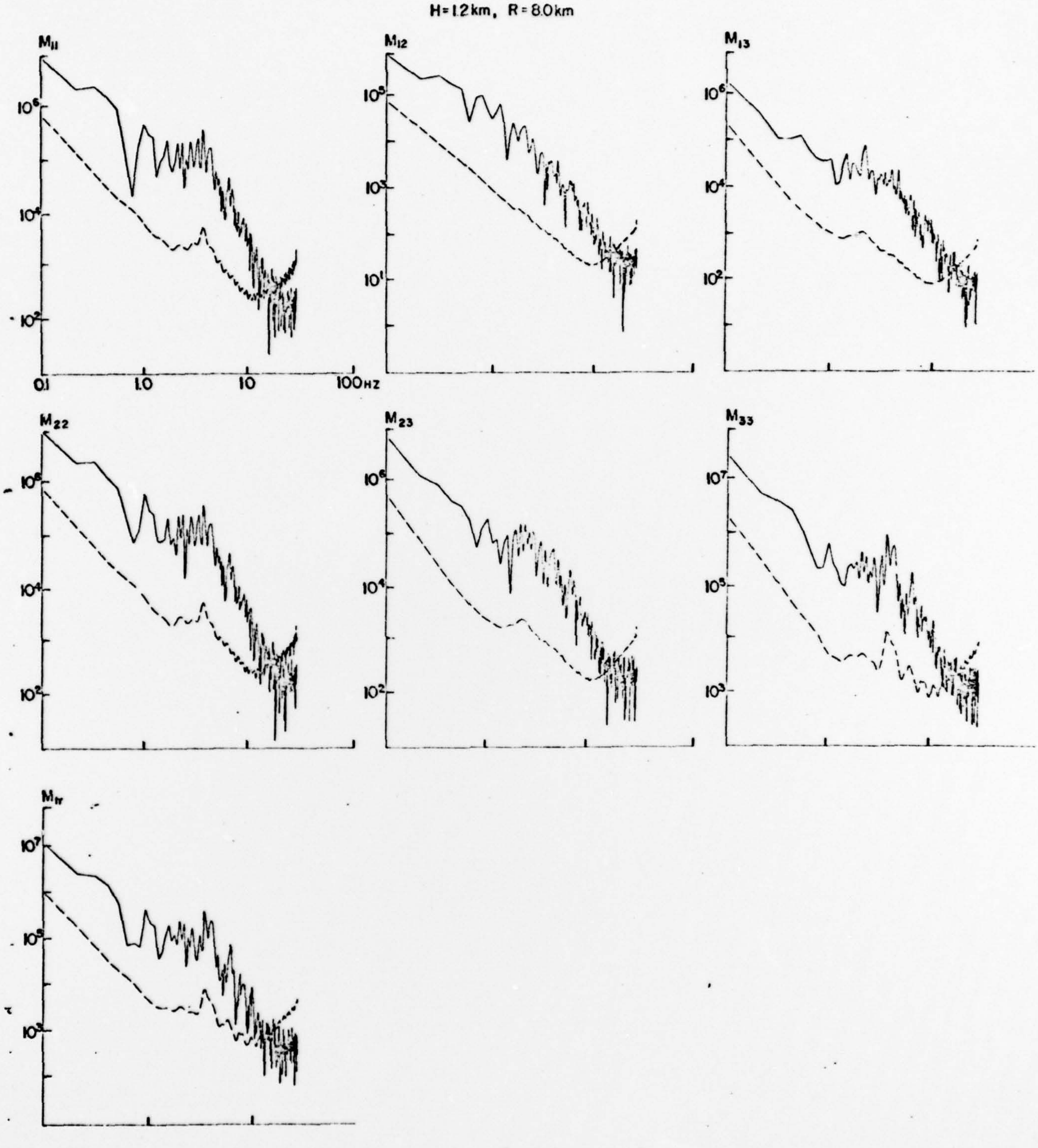

Figure 7. Amplitude density spectra (solid lines) of the components of the first time derivative of the moment tensor estimated for the JORUM collapse plus estimates of the standard deviation (dashed lines). The spectrum at the bottom is for the trace of the moment tensor.

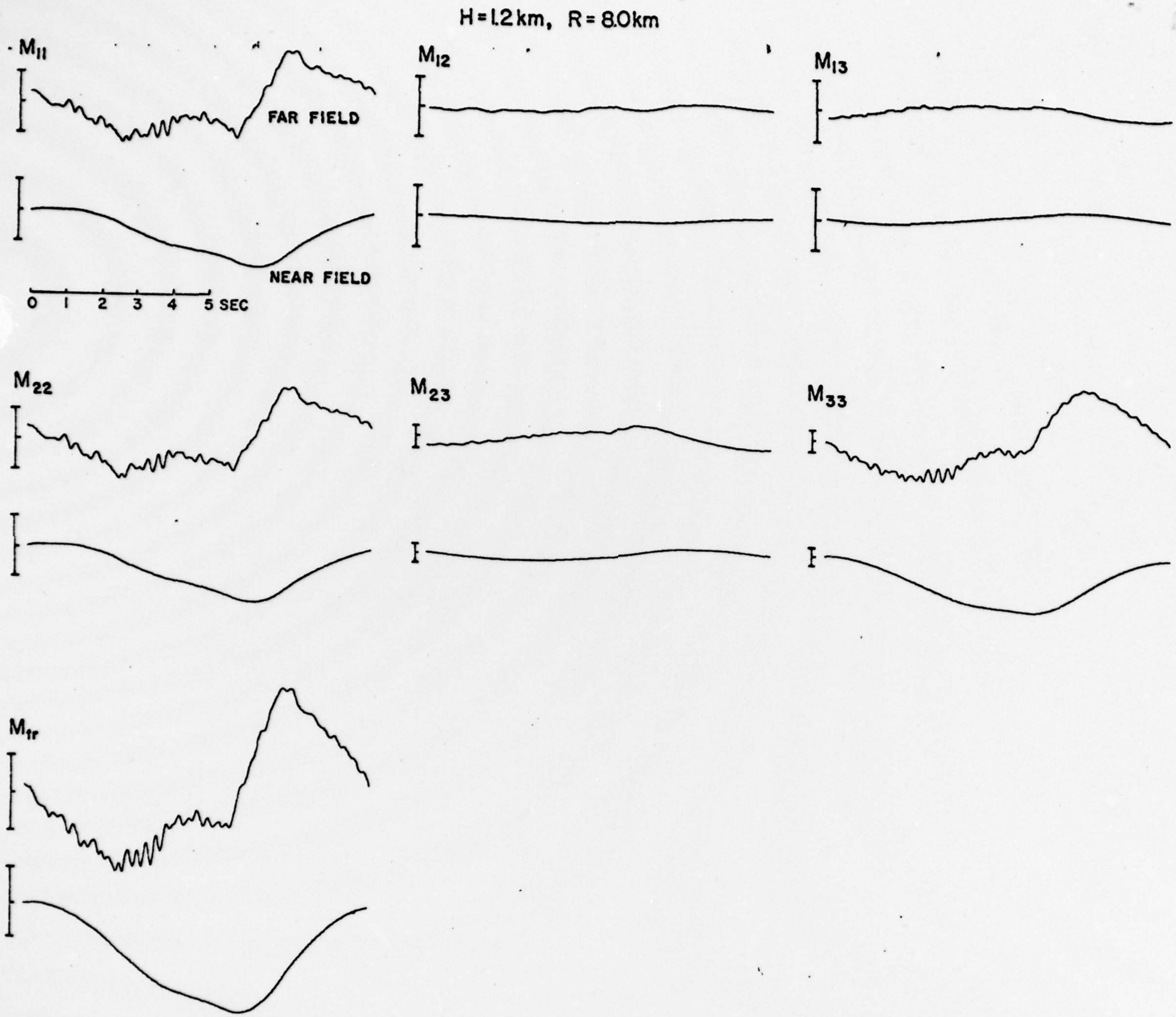

Figure 8. Estimates of the components of the moment tensor for the JORUM collapse in the time domain. The lower member of each pair is the component of the moment tensor and the upper member is its time derivative.